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MECHANICS OF WIND EROSION

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INTRODUCTION

The wind has been active as an erosive agent throughout geologic times. It takes soil from one place and deposits it in another. Outstanding examples are the extensive loess deposits in China and along the Missouri and Mississippi Rivers in this country.

Wind erosion has been active in some degree since prehistoric times but has become much more active and more destructive because of activity of man. This "accelerated" erosion has been due to wrong methods of handling the land or to use of the land for purposes to which it is not adapted.

Wind erosion is perhaps most active in arid and semiarid regions where the land surface is often dry and vulnerable to erosion and the protective vegetation is sparse or absent. But the wind may also move large quantities of soil material in humid regions; and, agriculturally considered, wind activity in such regions may be more important because of the greater value of much of the land affected.

The movement of soil by wind is a complex process influenced by conditions of wind, soil (including the nature of the eroding surface), amount of water in the soil, and many other factors. The cutting and transporting power of wind is determined by the interaction of several factors--some favoring soil movement, others opposing it. The activity in each individual case depends upon the net effect of these factors acting together. Soil material, in order to be transported by wind, must first be loosened from its position on the surface of the land. It may then be lifted, rolled, slid or bounced along on the surface of the ground. These processes are largely the result of wind turbulence, mainly eddies and irregularities of wind movement.

Differences in soil erodibility suggest that properties inherent in the soil and those brought about by land use--especially cultivation and other man-made disturbances--play an important part in the wind erosion process. Wind erosion is dependent directly on the physical character and condition of the soil. Only dry soils are moved. Wet or damp soils are not appreciably affected. The structure of the soil in an air-dry state is, therefore, a much more reliable index of erodibility than the structure in a wet state.

The amount of soil which is erodible by wind at a given velocity depends upon the critical height of and distance between the nonerodible fractions that are exposed at the surface (6).[1] The ratio of height of projections to distance between projections which will barely prevent the movement of erodible fractions is designated as the critical surface-roughness coefficient. Under a given wind velocity the critical-roughness constant remains the same for the whole range of size and proportion of the nonerodible clods. The critical surface-roughness constant required to assure soil stability, however, varies with other factors, such as the wind velocity and the size and apparent specific gravity of the erodible fractions. These factors, in the aggregate, add considerably to the complexity of the wind erosion process.

TYPES OF SOIL MOVEMENT

There are three types of soil movement in the process of wind erosion--(a) saltation, (b) suspension, and (c) surface creep. These usually operate simultaneously.

The movement of soil by wind is dependent not so much on forces at the surface as on the velocity distribution to such height as the grains rise in saltation. This height is definitely limited. Wind erosion is mainly a surface phenomenon and is not directly dependent on the condition of the wind beyond the restricted distance.

Movement of Soil by Saltation

Most of the soil carried by wind is moved in a series of short bounces called "saltation" (7). It is caused by the direct pressure of the wind on the soil particles and their collision with other particles.

After being pushed along the ground surface by the wind, the particles suddenly leap almost vertically in the first stage of the saltation movement (3). Some grains rise only a short distance; others leap 1 foot or higher, depending directly on the velocity of rise from the ground. They also gain considerable forward movement from the pressure of the wind upon them, and acceleration of horizontal velocity continues from the time the grains begin to rise until they strike the ground again. In spite of this acceleration, the grains descend in almost a straight line with an average angle of descent of between 6 to 12 degrees from the horizontal. On striking the ground, they either rebound and continue their movement by saltation or lose most of their energy by striking other grains--causing these to rise--and sink into the ground to form part of the movement in surface creep. Whether the movement is initiated by impact of descending particles or by impact of rolling grains, the initial rise of a grain in saltation is generally in a vertical direction.

The vertical rise appears to be due to two causes--the spinning of the grain and the steep velocity gradient near the ground (2). Grains carried in saltation may rotate at a speed of 200 to 1,000 revolutions per second; perhaps more than 75 percent of the grains carried by saltation spin.

The variation in air velocity near the ground causes a substantially higher rate of air flow at the upper than at the lower surface of a grain at rest on the ground surface. Consequantly, if the total difference in pressure between the upper and lower surfaces is greater than the force of gravity, the grain will rise in a vertical direction. This difference in pressure may be expected to intensify the spinning of the grain in a current of air.

After being shot into the air, the grains rise to varying heights and fall at accelerated speed as a result of gravity. On the whole, the vertical distance through which a grain

[1] Figures in parenthesis refer to Literature Cited.

continues to rise in saltation is about 1/5 to 1/4 the horizontal length of a single leap. The soil moved by saltation consists chiefly of fine grains ranging in diameter from 0.1 to 0.5 mm. The grains most easily moved by erosive winds range from 0.1 to 0.15 mm. in diameter. The removal in saltation appears to be the same for all soil types but some variation is found in the proportion of grains carried at different heights. Coarse granulated soils drift closer to the ground than more finely pulverized soils.

The relative concentration of soil particles at a given height remains the same under a wide range of wind velocities. The ratio of saltation to suspension decreases rapidly with height above ground. Grains in saltation do not generally rise higher than a few feet above the ground. Soil carried above this height is in true suspension and capable of being carried much higher and landing far from its original location. Virtually a straight-line relationship exists between height and the logarithm of the rate of flow in saltation and suspension over all soils (2).

Movement of Dust in Suspension

In the mechanism of soil transportation by wind, very fine dust particles less than 0.1 mm. in diameter are carried in true suspension. Such particles make up a substantial proportion of the total soil carried. They have a lower falling velocity than the upper velocity of the turbulent wind and are carried more or less parallel with the general wind direction. Their transportation has been termed "suspension movement." Small particles transported by suspension enter the air stream when the soil is bombarded by the saltation movement. Once entrained in the air stream they are suspended by the turbulence of the wind.

The presence of fine dust in suspension, even in large quantities, does not affect the general character of the movement in saltation or surface creep, but its presence in the soil greatly influences both the threshold wind velocity and the intensity of erosion for a given wind (2).

The mechanism by which the fine dust is lifted from the ground may be entirely different from that of saltation. Soils composed of fine dust particles are extremely resistant to erosion by wind. The movement of fine dust in an air current is mainly the result of saltation. Thus, without saltation movement, dust clouds would not arise except on a relatively limited scale as a result of disturbances by objects moving over the surface of the ground, or at the windward edge of an eroding area.

In contrast to the movement of grains in saltation, the movement of fine dust in suspension (after being lifted from the soil surface) is completely governed by the character of the wind movement. This fine dust is carried to great heights and long distances from its original location and thus may be considered a loss to the eroding area. On the other hand, the soil moved in saltation and surface creep usually remains within the eroding area or its immediate vicinity--especially when erosive winds blow from varying directions.

The proportion of soil moved by the three types of movement varies widely for different soils. Coarsely granulated soils erode by saltation and surface creep; finely pulverized soils, by saltation and suspension.

Movement of Soil in Surface Creep

Quartz grains of about 0.5 to 1.0 mm. in diameter are too heavy to be moved by saltation but are pushed along the surface by the impact of particles in saltation to form "surface creep" (1). Unlike grains in saltation, which receive most of their impact energy from the direct pressure of the wind, the grains moving in surface creep derive their kinetic energy from the impact of grains moving in saltation.

FORMS OF WIND EROSION

The wind erosion phenomenon may be more easily understood by recognizing the close interdependence of the five main ways in which soil particles are loosened and transported. These five ways may be considered as different phases of the same phenomenon.

Detrusion is the dislodgement of coarse soil grains from peaks or surface projections by wind pressure or by the bombarding action of highly erosive grains coming from the windward side.

Effluxion is the removal of soil grains ranging from 0.05 to 0.5 mm. in diameter, and is initiated and maintained by the direct pressure of the wind. The removal is almost entirely by saltation, but a minor portion of the soil may be removed in surface creep, and some fine particles may be picked up directly by the wind and carried away in true suspension.

Extrusion is the forward thrust of soil particles which are too coarse to be removed by direct wind pressure. If a field composed of these particles has on its windward side an area containing particles removable by effluxion, many of these coarse fractions may be removed as a result of bombardment by the smaller grains. Extrusion is carried out chiefly by surface creep.

Efflation is the removal of soil in suspension, resulting mainly from movement of coarser grains in saltation. It is serious because it constitutes a removal of fine soil constituents, leaving the less mobile and inert sand and gravel behind.

Abrasion is the chipping off of particles of dust and coarser fractions from soil clods and other hard materials as a result of impacts from grains moving in saltation.

Some or all of these forms of erosion may be operating at the same time. However, none of them can exist without effluxion. In other words, effluxion is a prerequisite to and cause of the other forms of wind erosion. Therefore, a program of wind erosion prevention and control should be based on either reducing the amount of particles ranging from 0.05 to 0.5 mm. in diameter in a soil to an allowable minimum, or protecting the soil from the erosive force of the wind.

WIND EROSION PROCESS

The wind erosion process consists, in general, of three distinct phases--(a) initiation of the movement of soil particles, (b) their transport, and (c) their deposition (9).

The wind acts as a fanning mill on the soil--removing organic matter, fine silt and clay fractions, and leaving behind sand and gravel (fig. 1). This sorting action, when continued year after year, tends to make a soil coarser in texture and consequently more erodible and less productive than it was originally.

In addition to the sorting action of wind the intensity of the movement increases progressively with distance across eroding areas (5). The intensity of the movement at the windward edge of an eroding area, whether it be the edge of a field or the beginning of a highly erodible spot in the field, is approximately zero. From this point the amount of soil being moved may increase progressively up to certain limits if no obstruction or trap of any kind intervenes.

The gradual increase in the amount of soil movement toward the leeward side of eroding areas may be identified by certain easily recognized earmarks: (a) the progressive accumulation of erodible soil grains toward the leeward side of the eroding areas, (b) the gradual decrease in surface roughness resulting from the leveling-down process or detrusion, and (c) the cumulative degree of abrasion of the surface crust or clods caused by impacts from saltation.

The increasing intensity of soil movement downwind across eroding areas has an important bearing on plans and measures for controlling wind erosion. It points to the importance of trapping the soil where it first starts to move; the value of trap strips, such as those employed in "wind stripping" in reducing the amount of erosion by wind; and the need for community action in preventing the spread of wind erosion to unaffected areas. Wind erosion in some respects is like an epidemic disease. It must be controlled at its source before it gets out of hand entirely.

Initiation of Soil Movement

Surface winds are turbulent for all velocities over approximately 2 miles per hour (11). Turbulence of the wind in the open is indicated by irregular velocity fluctuations known as "gusts." This turbulence, together with velocity, is responsible for starting the movement of soil in the wind erosion process.

The minimum velocity of wind required to initiate soil movement is known as threshold velocity (1). The greatest single factor influencing the threshold velocity is the size of the soil grains (3). The threshold velocity is the lowest for grains 0.1 to 0.15 mm. in diameter. These require a velocity of 8 to 9 miles per hour at 6 inches above the ground. The threshold velocity increases with either an increase or decrease in the size of grains from these diameters.

The high resistance of fine dust particles to erosion by wind appears to be due partially to cohesion but mainly to the fact that the particles are too small to protrude above a laminar and viscous layer of air close to the surface of the ground. Fine dust is lifted from the ground mainly by impacts of larger grains, which are more erodible because they protrude farther into the fast moving, turbulent currents of higher air. Due to cohesion, the threshold velocity is lowered considerably by the presence of dust mixed with coarser grains.

The threshold velocity for undecomposed crop residues and weeds, even when these are merely scattered on the surface of the ground, is higher than for most of the erodible soil grains. Thus, if the wind is not too strong, some or all of the drag is absorbed by this material and erosion of the soil is reduced considerably; but if the wind is strong enough to remove crop residues, the threshold velocity at the affected surface is reduced and movement of the soil will continue under lower wind velocity than previously.

In like manner, the minimal threshold velocity for bare fields and for fields that are unprotected by crop residues from the start is usually much higher for the first windstorm than for succeeding ones. This may be due to several reasons. A thin surface crust which is not easily eroded may become completely disintegrated under continued abrasion by loose grains and thus lose its protective value. On cultivated soils the sorting action of the wind may result in accumulations of dunes which have a much lower threshold velocity than the uneroded soils (fig. 2). The threshold velocity for dune materials is lowest and varies little with soil type.

There is, therefore, a range of threshold velocities for any soil, depending on the previous history of the field. This range varies from 13 to at least 30 miles per hour at a height of 1 foot above smooth ground surfaces.

FIGURE 1.--The wind acts as a fanning mill--removing organic matter, fine silt and clay fractions.

FIGURE 2.--Dunes formed by surface creep. Soil in this field was blown out to a depth of 4 feet during a raging dust storm.

Erosion, once under way in a field, is maintained by impacts of particles moving in saltation and not by the direct pressure of wind against the ground, except on the extreme windward edge of the eroding area. Knolls, ridges, sand pockets, and areas with very limey soils start to erode at a lower wind velocity than other parts of a field. But when erosion starts, it spreads fanwise to leeward and the bombarding action of the particles in saltation causes movement of soil in areas which would otherwise remain in place under an equal wind velocity. The minimum threshold velocity for the less exposed parts of a field is therefore determined by the minimum threshold velocity for the most exposed or most erodible spots and is consequently equal to the minimum impact required to dislodge particles rather than the minimum fluid threshold velocity.

For the initiation of particle movement on desert sand by wind, a "static-threshold wind" depends on (a) the former history of the surface, (b) the extent to which the sand removed has collected to form a protective layer with the largest grains on the surface, (c) the surface turbulence of the wind, and (d) the length of the exposed surface (1).

Once particles begin to move, a "dynamic-threshold velocity" lower than the static-threshold velocity maintains continued particle movement downwind. This behavior may be likened to the action of the particles as projectiles which rebound upon striking the surface and continue their movement downwind or cause the movement of one or more other particles upon striking the surface.

Transportation of Soil

The lifting of loose material lying exposed on the surface is largely the work of eddies and irregularities of movement in the wind. The air currents are exceedingly variable and made up of many cross currents and eddies. The movement is, in fact, very complex, and there is much mixing of air molecules except in the exceedingly thin layer of air at the surface. The numerous momentary currents of the wind blow up and down as well as horizontally. Wind direction is the result of this great variability. It characterizes the general movement of the whole air mass rather than its motion at any particular point and instant. These eddies and cross currents are of great importance in promoting the thorough mixing of the atmosphere and enabling it to lift fine material from the surface of the ground. The threshold velocity depends on the maximum momentary velocity of turbulent flow, not on the average forward velocity. Eddies are thus of greater importance in lifting and transporting soil than is the average velocity of the wind.

It has been found that the rate of sand movement varies directly with the range of size of the erosive grains and the square root of their average diameter (1). The rate of soil movement depends little on the density of the air, but varies greatly with the drag velocity, and with the degree of gustiness of the wind. The rate of soil movement in saltation, suspension, and surface creep varies as the cube of the drag velocity of the wind (4).

The ability of the wind to transport soil is enormous. The carrying capacity of the winds blowing over the basin of the Mississippi River, for example, has been estimated to be 1,000 times the transport capacity of the river (10). It has been calculated that the wind storms strong enough to create dust storms during a 12-month period in the Western States would be equivalent to at least two strongly active dust storms of high soil-carrying capacity annually, each lasting 24 hours. Assuming an average wind velocity in the lowest mile in the atmosphere to be 30 miles per hour, the carrying capacity of these storms would be equivalent to about 853,700,000 tons of dust carried about 1,440 miles. During such a period the wind would accomplish about 1,229,342,400,000 ton-miles of transport.

The estimated load of sand and dust that may be carried by the atmosphere ranges from 150 to 126,000 tons per cubic mile of air, depending on the velocity of the wind. A dust storm on March 25, 1895, was estimated to have loaded the atmosphere with 1,600 tons of dust per

cubic mile of air at Rock Island, Ill. (8).

The capacity of the atmosphere for transporting particles of soil smaller than 0.1 mm. in diameter is very great. It has been estimated that 1 cubic foot of air, agitated to an average velocity of 5 miles per hour, is capable of sustaining the following amounts of soil (9).

Average diameter of particles	Weight of soil per cubic foot of air
Millimeters	*Grams*
0.08	0.020
.04	.057
.007	.118
.001-	.530

Measurements of the concentration of wind-borne particles indicated that most of the soil movement in saltation was carried below the height of 2 to 3 feet (2). In fact, over 90 percent of the soil was transported below the height of 12 inches. Over 50 percent of it remained below the 2-inch level. The rate of flow at the 0- to 38-inch height amounted to about 490 pounds per hour per 1-foot width for an 18-mile-per-hour wind and 990 pounds for a 25-mile-per-hour wind.

Wind erosion of a soil which ranges in composition from fine clay and organic particles to larger soil grains gives rise to all modes of transport. Fine particles in suspension are lifted to great heights.

As much as 200 pounds of dust per acre, which originated in the Texas-Oklahoma Panhandle region after a dust storm on February 7, 1937, was deposited on snow in Iowa 500 miles away. Analysis of samples of the "black" snow showed that the deposits contained three times as much humus as the best soil remaining in the source region of the storm.

Soil particles, after being lifted from the surface (except the very fine dust that becomes part of the atmosphere), eventually come to rest again when the wind subsides or when surface obstructions alter the velocity distribution and turbulence structure.

Soil material moved by wind and deposited in dunes has an average diameter range of approximately 0.16 to 0.35 mm. and constitutes only a part--though a major part--of the total movement. Fine dust, once lifted into the air, may be carried great distances from the eroding area. On sandy soils the fine particles usually make up a minimum part of the total volume of soil moved in comparison with the amount moved along the surface of the ground. In some cases, however, the removal of the finer particles constitutes a much more serious aspect of the wind erosion problem on these soils. In contrast, the "hardlands" seem to break down to their primary particles and go into suspension. This often results in the removal of the whole soil mass.

Smaller soil particles, within specific limits, are more easily moved by the wind. Consequently, in attacking a heterogeneous deposit, the wind tends to remove the finer particles and leave the coarser ones.

The gradual increase in the rate of soil movement with distance away from the windward edge of eroding fields is due mainly to (a) the steadily increasing amounts of erosive particles, and (b) the cumulative degree of abrasion along the direction of the wind (3).

The steadily increasing accumulation of erodible soil fractions on the ground surface toward the leeward side of eroding fields produces a condition that is increasingly more susceptible to erosion by wind until, for material composed only of erodible fractions, the rate of soil flow is the highest possible for the particular soil and wind velocity

The second factor accounting for increased soil movement is the cumulative degree of abrasion resulting from impacts of grains in saltation. As the concentration of erodible grains increases gradually to leeward, so likewise does the rate of break-down of soil clods and surface crust increase. These break down into fractions which are fine enough to abrade and erode more soil clods and surface crust in their journey with the wind.

Deposition of Atmospheric Load

Material carried in either suspension or saltation is deposited primarily when the wind velocity decreases (fig. 3). However, due to the variable character of the wind, and indeed to the very nature of the process of saltation, the process of picking up and depositing material is virtually continuous. Most problems connected with the process of accumulation of blown material are caused by retention of the material which is deposited. Since both the removal and transportation of material depend upon the violence of the wind, the problems of retention in the final analysis are closely related to wind velocity. Whatever helps to decrease wind velocity will favor retention as well as deposition. Thus vegetation and other surface obstructions, by decreasing the wind velocity, not only cause the wind to deposit its suspended matter but also prevent the wind from picking it up again.

Because of their retentive ability, plants are particularly efficient in collecting drifting sand and other material moving along the surface in a series of short leaps (fig. 4). A clump of plants in an area of moderate sand drift will thus collect blown material around it, forming a small mound. As the sand heap grows, the plants, if adapted to sandy soil, also grow and continue to accumulate soil until a heap several feet high may be formed.

It is obvious that mounds may also be produced by the removal of soil from the spaces between plants instead of by accumulation of soil brought in from more distant places and deposited around the plants. In fact, in the case of desert mounds, both forces may be at work at the same time. Because of the great mobility of the surface material, mounds in plant-protected spots tend to grow rapidly at the expense of the interspaces which lack this advantage. The wind is only one cause of this growth.

Decrease of wind velocity and consequent deposition may be due to conditions not connected with vegetation or other surface obstacles, but which are much more general and affect much larger areas. The more or less constant winds caused by climatic and other general meteorological conditions or by large topographical features are known to lose their velocity habitually in certain areas. If these winds are dust laden, such areas will become areas of aeolian deposition. Of course, there must be somewhere complementary areas of aeolian removal from which the winds have obtained their load. The accumulation of aeolian material over wide areas depends in the most complex way upon climatic factors--not only as they influence the path and velocity of the wind, but also as they control the presence or absence of vegetation and its nature and permanence.

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FIGURE 3.--This fence caused the soil-laden wind to deposit a major part of its load by decreasing its velocity.

FIGURE 4.--A ton or more of growing plants or crop residue per acre has prevented wind erosion damage during severe windstorms.

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